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Aircraft Active Microwave Measurements for Estimating Soil Moisture

A correlation between the C band scatterometer data and soil moisture of 0.81 was found for an angle of incidence of 15 degrees.

Abstract: *Previous research has shown that active and passive microwave sensors can be used to estimate near-surface soil moisture. An advantage of the active systems is that they have the capability of high spatial resolution from satellite platforms. Most of the previous research has been conducted on agricultural fields. This study examined the use of active microwave data for estimating the average surface soil moisture for several watersheds located near Chickasha, Oklahoma. Data were collected using P, L, and C band scatterometers, mounted on the National Aeronautics and Space Administration C130B aircraft flying at an altitude of 300 m. Soil moisture data were collected in conjunction with three flights during May 1978. Our results indicated that relationships between the scatterometer data and soil moisture do exist and agree with the results obtained in previous experiments.*

Introduction

Research has shown that both active and passive microwave sensors are sensitive to variations in near-surface soil moisture. Each type of system has advantages and disadvantages. The principal advantage of active microwave systems for soil moisture applications is that high spatial resolution can be retained even at satellite altitudes. Its disadvantage is the time and cost of processing these data in large scale studies. Passive systems have much lower spatial resolution at satellite altitudes because of design limitations; however, processing these data is much easier.

In this study, we examined the use of active microwave scatterometers operating in three bands for estimating near-surface soil moisture within several watersheds from an aircraft platform. Although considerable research has been conducted using ground level platforms, only a few studies have utilized aircraft. The three scatterometer bands, P, L, and C used are described in Table 1.

Active Microwave-Soil Moisture Relationships

Microwave scatterometers measure the backscatter from the radar pulse in the direction of the source. This situation is represented schematically in Figure 1. The response is expressed as a backscattering coefficient, σ^0. The magnitude of σ^0 depends upon the surface characteristics (small and large scale roughness) and dielectric properties of the target. The link to soil moisture is through the dielectric properties that have been found to be dependent on moisture content (Cihlar and Ulaby, 1974). The soil moisture relation-

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TABLE 1. SCATTEROMETER FREQUENCIES

System designation	Frequency	Wavelength
	GHz	*Cm*
C band	4.75	6.3
L band	1.60	18.9
P band	.40	74.9

ships also depend upon system parameters. These include the wavelength, polarization, and incidence angle.

Extensive ground based experiments have been conducted, primarily at the University of Kansas, to evaluate and quantify the performance of active microwave systems for measuring soil-moisture related parameters under a variety of conditions. Target parameters investigated have included the effects of surface roughness (small scale factors, such as tillage), vegetation, and soil texture. Sensor parameters have included band frequency, polarization, and incidence angle.

Ulaby *et al.* (1978) presented results from a series of truck mounted scatterometer experiments designed to analyze all of the factors described above. Under bare soil conditions, they measured σ^0 at eight wavelengths ranging from 4.1 to 27.2 cm at incidence angles between 0 and 40 degrees for various polarizations. Several surface roughnesses and soil textures were sampled. Figure 2 is a plot of σ^0 versus the 0 to 1 cm gravimetric soil moisture content for all the C band samples for the system. The best overall linear correlation was between soil moisture and σ^0 at a wavelength in the C band at a 10 degree incidence angle when using horizontal transmit-horizontal receive (HH) polarization. They arrived at this conclusion by analyzing plots, such as Figure 3, that show the correlation coefficient as a function of angle of incidence for the different frequencies and the sensitivity of the σ^0 - soil moisture relationships.

Experiments, designed to isolate and quantify the effects of soil texture (Dobson and Ulaby, 1979), indicated that texture did influence the soil moisture - σ^0 relationship and that its influence

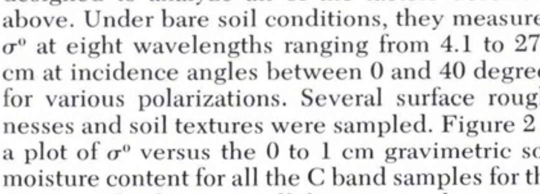

FIG. 1. Radar backscattering for rough and smooth surfaces.

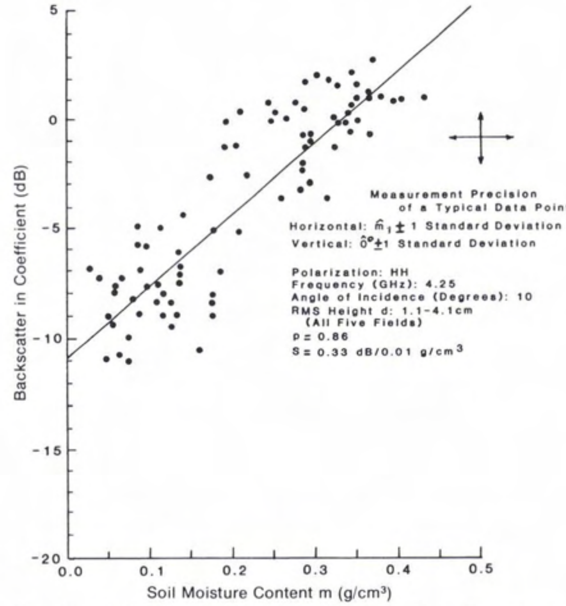

FIG. 2. Relationship between volumetric soil moisture and backscattering coefficient for 84 University of Kansas data sets (Ulaby *et al.*, 1978).

could be offset by using the relationships between σ^0 and moisture tension. Linear correlation values were high for individual sites when σ^0 was related to gravimetric or volumetric soil moisture or moisture tension. However, when they combined all the sites, the gravimetric and volumetric soil moisture - σ^0 correlation decreased significantly whereas the moisture tension - σ^0 relationship remained high. This would support the use of a moisture tension based relationship. However, their results also show that textural effects become more significant as the textural types become more diverse. Thus, within a region it may not be necessary to consider texture.

Ulaby *et al.* (1979), who also considered the effects of vegetation, found that the optimal sensor system was the same as for bare soil, regardless of the crop type. When combining these data with those for bare soil, the linear correlation between σ^0 and percent of field capacity was about 0.8, using a truck mounted scatterometer system, regardless of the depth of soil moisture used; however, based on their bare soil results, they suggest using the 0 to 5 cm depth average.

Only a few experiments using aircraft mounted active microwave systems to determine soil moisture have been conducted. Several extensive data sets have been collected recently but are still being processed. Cihlar *et al.* (1975), who obtained soil moisture data over bare fields in Phoenix, Arizona using imaging L and X band radar at angles of incidence ranging from 43 to 57

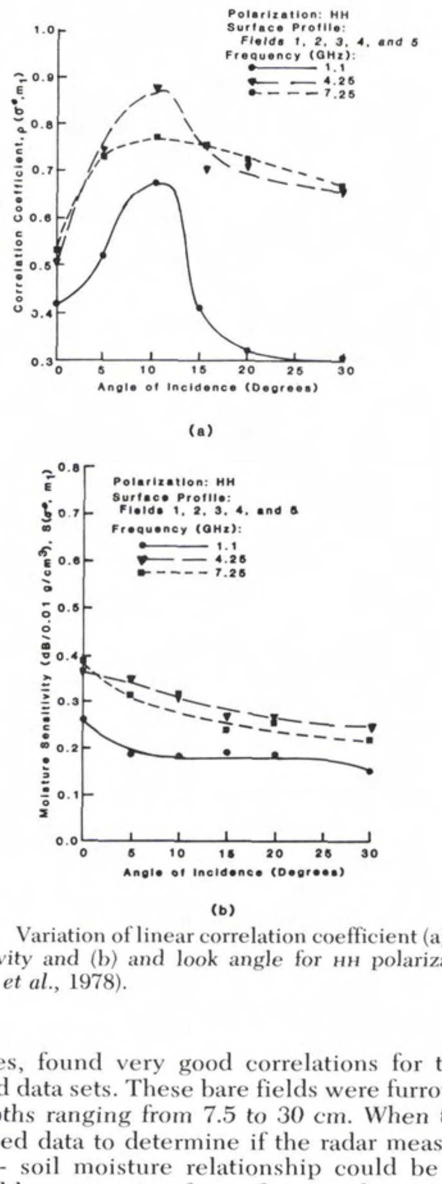

FIG. 3. Variation of linear correlation coefficient (a) and sensitivity and (b) and look angle for HH polarization (Ulaby *et al.*, 1978).

degrees, found very good correlations for their limited data sets. These bare fields were furrowed to depths ranging from 7.5 to 30 cm. When they analyzed data to determine if the radar measurement - soil moisture relationship could be improved by accounting for surface roughness, they found that scatter was still significant after separation into groups. When they subdivided these fields into four groups based upon furrow depth to study macroscale roughness effects, they found no apparent relationship.

Blanchard (1979), who used L and K band scatterometers at an altitude of 500 m over sites with silty and fine sandy clay loam in Texas, found that vegetation had the greatest influence at angles of incidence near nadir and beyond 25 degrees. He obtained better relationships between σ^0 and volumetric soil moisture using the L band system for both bare and vegetated fields. The best correlation was 0.84 for the L band system at 20 degrees.

EXPERIMENTAL DESIGN

A series of aircraft flights were flown on 1, 12, and 30 May 1978 over watersheds located near Chickasha, Oklahoma. The sensor platform was the National Aeronautics and Space Administration C130B aircraft flying at an altitude of 300 m and at ground speed of 275 km/hr.

Three scatterometers, placed on the aircraft, were operating in C, L, and P bands (Table 1). Their beam patterns along the flight path were fan shaped, which allowed for angles of incidence between 5 and 60 degrees. Ground spot sizes were processed to between 40 and 75 m along track, depending on the sensor. Crosstrack resolution depended on the beam width and altitude of the sensor. At the 300 m altitude, resolutions were about 30, 45, and 70 m for the C, L, and P bands, respectively. Although both HH and HV polarizations were used, only HH data were processed.

Five flightlines were flown that covered a total of nine watershed units. These study sites included a wider variety of cover conditions and topography than did previous studies. Three gently sloping (about 0.3 percent) agricultural fields were sampled; C3 and C4 were fallow and C5 was in mature winter wheat. Six rangeland or pasture watershed groups were also sampled. Watersheds R5 and R6 were well managed with drainage slopes of 5 percent and moderate topographic variations on the slopes, whereas F1 and F2 were gently sloping (about 2 percent). Watersheds R7 and R8 had topography similar to R5 and R6, but were poorly managed and eroded. All watersheds had some type of clay loam soil and ranged in size from 0.08 to 0.12 km². Additional details on these sites, including topographic and soils maps, can be found in Jackson *et al.* (1980).

Gravimetric soil moisture samples were obtained in each watershed at depths of 0 to 2.5, 2.5 to 5, and 5 to 15 cm. The number of soil moisture samples taken for each field varied from 12 to 100 but was typically 25. Soil moisture data were processed to compute gravimetric soil moisture for three depths from the surface: 0 to 2.5, 0 to 5, and 0 to 15 cm. Later, bulk density samples were collected to convert the gravimetric samples to volumetric soil moisture. All samples within a watershed were averaged for each depth-date-site combination. Generally, all soil moisture samples were obtained within one hour of the aircraft overflight.

RESULTS AND DISCUSSION

Scatterometer data were processed for the three wavelengths at angles of incidence from 5 to 50 degrees at 5 degree intervals. No calibration of the sensors was performed between the flights. Due to equipment failure, no data were available for C band on 1 May. Scatterometer data were averaged for the time periods when the aircraft was over the watershed. A relatively wide range of soil moisture values was observed for each flightline and for most watersheds. Between 15 and 23 samples were available for each relationship. Data collected over the C watershed group on 30 May were deleted due to standing water conditions that produce specular returns.

Linear correlation analyses were performed to relate the backscattering coefficient to the volumetric soil moisture for each band, depth of measurement, and incidence angle. Figures 4a, b, and c show the results of this exercise. Several patterns are apparent. We observed that for any band and depth of measurement the general trend was for the correlation to increase to a maximum at about a 10 to 15 degree angle of incidence. This is similar to the results obtained at the University of Kansas. For all situations, the best results were obtained by using the C band system. L band provided the second best results. These results also support those obtained at the University of Kansas. One of the most interesting results we observed was the improvement in the linear correlation of the C band relationship when a deeper depth of measurement was used. The correlations for the 0 to 2.5, 0 to 5, and 0 to 15 cm depth of measurements were 0.62, 0.69, and 0.81, respectively, at an incidence angle of 15 degrees. Previous investigation had not observed this particular pattern of increasing correlation with depth of measurement. We concluded that the higher variability of the surface soil moisture contributed to the distribution of the observations about the backscattering coefficient - soil moisture relationship. Because the variability of the soil moisture decreased with depth in these experiments and the soil moisture in the surface layer is usually correlated with the soil moisture in lower layers, the pattern does not seem unreasonable.

From Figure 4 we concluded that the best relationship was for C band at an angle of incidence of 15 degrees and correlated with the 0 to 15 cm volumetric soil moisture. The plot of the data and the regression line for this relationship is shown in Figure 5. The correlation for this relationship is approximately the same as that obtained by the University of Kansas for all of their bare and vegetated fields (Ulaby *et al.*, 1979) which supports both sets of results.

To determine the sensitivity of the σ^o to the volumetric soil moisture, we examined the units of change of σ^o for each unit of change of soil moisture, in a manner similar to the analysis conducted by Ulaby *et al.* (1978) and presented in Figure 3b. The C band scatterometer sensitivity operating at a 15 degree angle of incidence was 0.44 dB/(percent volumetric soil moisture). This result can be compared to a value of 0.33 obtained by Ulaby *et al.* (1978). Although the two values are similar, the aircraft measurement would suggest a greater sensitivity to soil moisture than that observed in the truck experiments. Part of the difference in the values may be attributed to the difference in the soil layer used. To test this effect, the sensitivity of

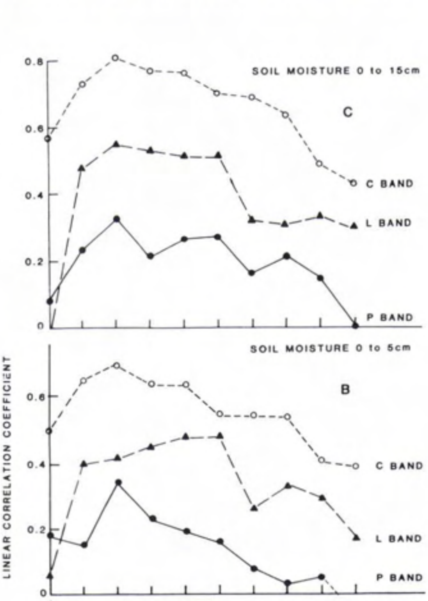

FIG. 4. Variation of linear correlation coefficient of volumetric soil moisture and backscattering coefficient as a function of look angle, wavelength, and depth of measurement of soil moisture.

FIG. 5. Relationship between volumetric soil moisture (0 to 15 cm) and backscattering coefficient for Chickasha, Oklahoma watersheds.

the same aircraft system to the 0 to 5 cm soil moisture was computed. This value was 0.345 dB/(percent volumetric soil moisture) which is very close to the University of Kansas value for the same measurement depth. The increased sensitivity can be explained mathematically by considering two points. First, the dynamic range of the σ^0 measurements remains the same regardless of the depth of soil moisture used. Second, the range of soil moisture values decreases with depth of measurement due to decreased variability. These two facts lead to an increased slope of the σ^0 soil moisture relationship with increasing depth of measurement.

Overall, the level of correlation was similar to those obtained in the University of Kansas field measurement studies. One source of variation that was expected to reduce the correlation between σ^0 and soil moisture was the heterogeneity of land cover within some of the watersheds. Although the cover was relatively homogeneous, variations did exist that added noise to the relationships. This problem was compounded by the narrow beam width used and the fact that it was impossible to fly over exactly the same path each time.

Another obvious possible source of variation was the topography of the watersheds. Some watersheds were smoothly sloping, the C group, whereas others, the R group, had a moderate degree of natural variation. Because of the problems described previously concerning land cover and the importance of surface geometry in active microwave return, a reduction in correlation was expected but not observed.

Considering the problems described above, our results are encouraging. Because no other results are available for similar sites, our conclusion must be based on limited data. Additional data have been collected at these and other sites, and when they have been processed, our analysis will be updated.

Summary

Microwave scatterometer data were obtained during a series of three aircraft flights over a group of Oklahoma research watersheds during May 1978. Data were obtained for the C, L, and P bands at angles of incidence between 5 and 50 degrees. Supporting measurements of soil moisture were made on the days of the overflights. Linear correlation analyses were performed to relate the backscatter coefficient with the volumetric soil moisture in the three soil layers. The best results were obtained using C band data at incidence angles of 10 and 15 degrees and a soil moisture depth of 0 to 15 cm. These results were in excellent agreement with the conclusions of the truck mounted scatterometer measurement program performed at the University of Kansas (Ulaby *et al.*, 1978; 1979).

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